Accretion–ejection phenomena from young stars

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ABSTRACT

In the current paradigm of star formation magnetic fields play a very central role. Indeed, they probably help or even channel the initial gravitational collapse of the parent molecular cloud. But their most spectacular effect is certainly the production of ubiquitous, powerful, bipolar self-collimated jets. Also, in the last decade, evidence has come that in such systems a magnetosphere links the protostar to its surrounding accretion disc.

I will first briefly review the magnetohydrodynamic models of jets from young stars. Then, I will discuss some constraints on the magnetospheric interaction since accretion must proceed despite strong stellar magnetic fields. Finally, I will introduce the 3Reconnection X-wind" scenario that leads to episodic jet formation with efficient removal of protostellar angular momentum.

1. Introduction

Collimated ejection of matter is widely observed in several astrophysical objects: inside our own galaxy from all young forming stars (Hartigan et al. (1995)) and some X-ray binaries (Mirabel and Rodriguez (1999)), but also from the core of active galaxies (Cao and Jiang (1999), Jones et al. (2000)). All these objects share the following properties: jets are almost cylindrical in shape; the presence of jets is correlated with an underlying accretion disc surrounding the central mass; the total jet power is a sizeable fraction of the accretion power.

Most of observed images show jets that are extremely well collimated *already close to the source*, with an opening angle of only some degrees. On the other hand, the derived physical conditions show that jets are highly supersonic. Indeed, emission lines require a temperature of order 10^4 K, hence a sound speed $c_s \sim 10$ km/s while the typical jet velocity is $v_j \sim 300$ km/s. The opening angle θ of a ballistic hydrodynamic flow being simply $\tan \theta = c_s/v_j$, this provides $\theta \sim 5^o$ for YSOs, nicely compatible with observations. Thus, observed jets could well be ballistic. Note that this qualitative argument is not changed by recent observations

of rotation in jets, since the rotation velocity is of the same order than the sound speed (Testi et al. (2002)).

Therefore, the fundamental question is *how does a physical system produce an unidirectional supersonic flow ?* This implies that confinement must be intimately related to the acceleration process. To date, the only physical process proved to be capable of accelerating plasma along with a self-confinement relies on the action of a large scale magnetic field (carried along by the jet). Such a magnetic field is assumed to arise from either advection of interstellar (fossil) magnetic field or from local dynamo (or both).

There are three different situations potentially capable, at all evolutionary stages[1], of driving magnetized jets from young forming stars:
• **The protostar alone**: stellar winds extract both energy and mass from the protostar itself (Sauty et al. (2002)).
• **The accretion disc alone**: "disc winds" are produced from a large radial extension in the disc and are fed with both mass and energy provided by accretion (Casse and Ferreira (2000a)).
• **The interaction zone between the disc and the protostar**: "X-winds" are disc-winds produced in a tiny region around the magnetopause between the disc and the protostar (Shu et al. (1994), Lovelace et al. (1999)).

Pure stellar wind models are less favoured because observed jets carry far too much momentum. In order to produce an observed jet, a protostar should be either much more luminous or rotating faster than observations show (DeCampli (1981), Konigl (1986)). Unless otherwise proven, this leaves us with either disc-winds or X-winds. Note that what distinguishes these last two scenarii is mainly belief: belief that no significant large scale magnetic field could be found in the innermost disc region (up to a few au). It is however possible to observationaly discriminate between them (Shang et al. (2002), Garcia et al. (2001b)). Nevertheless, the disc-wind scenario is usually favoured because it offers an "universal" paradigm able to explain jets from several astrophysical objects without relying on the central object.

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[1]The evolutionary scenario of a young forming star goes from Classes 0, I (embedded source) to Class II (optically visible Classical T Tauri star) and Class III (Weak line T Tauri star: no signs of accretion/ejection). The correlation between accretion and ejection remains valid from Class 0 to Class II phases (Cabrit et al. (1990), Hartigan et al. (1995), Bontemps et al. (1996)).

2. Accretion–ejection from circumstellar accretion discs

2.1. The disc ejection efficiency

A large scale (mean) magnetic field of bipolar topology is assumed to thread an accretion disc, allowing ejected plasma to flow along open field lines. This field extracts both angular momentum and energy from the underlying disc and transfers them back to a fraction of ejected plasma. This plasma is accelerated from the disc surface by the so-called "magneto-centrifugal force" and, farther away, is self-collimated by the magnetic "hoop-stress" (see Ferreira ((1997)) for an explanation). Accretion and ejection are therefore interdependent, which requires a new theory of accretion discs. Indeed, one must solve the disc vertical structure[2] as well as the radial one, ie. the full 2D problem. This is the reason why no toy-model has been able yet to catch the main features of these accretion–ejection structures.

In these accretion discs, because mass is being lost in the jets, the accretion rate varies with the axial distance such that

$$\dot{M}_a \propto r^\xi \tag{1}$$

where ξ measures the ejection efficiency (Ferreira and Pelletier (1993)). While the standard accretion disc model is characterized by $\xi = 0$, a revisited theory of ejecting discs provides the allowed values of ξ as a function of the disc properties (Casse and Ferreira (2000a)). In turn, ξ fixes the amount of mass that is actually ejected by the accretion disc. It turns out that the overall jet behaviour (asymptotic jet radius and velocity, degree of collimation) drastically depends on this load (Ferreira (1997), Ouyed and Pudritz (1999)). There has been quite a lot of work done on the area of jet launching from keplerian accretion discs, but only very few addressed explicitly the problem of mass loading into the jet[3], ie. the value of ξ. To my knowledge, apart from the work reported here, only Wardle and Konigl ((1993)) and Li ((1995)) did it, but they used crude approximations forbidding them to get the physically acceptable range in ξ (see Ferreira ((1997)) for a detailed discussion).

2.2. Self-similar models

Answering this can only be done by constructing a self-consistent accretion–ejection model, from the resistive MHD accretion disc to the ideal MHD jet. Dealing with the partial

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[2]Jet models of eg. Blandford and Payne (1982) or Pelletier and Pudritz (1992) treated the disc as a boundary condition.

[3]This holds also for X-wind models.

derivatives involves the use of self-similar solutions[4] following the scaling imposed by the gravity of the central object (Ferreira and Pelletier (1993)). The validity of such solutions is questionable if jets arise from a small region in the disc. However, if jets are launched from a large region (say between 0.1 and a few au), then they provide a correct description. In what follows, I describe some key features of such accretion disc models and recommend the interested reader to refer to the series of published papers.

The accretion disc must be resistive enough so that matter, which is both rotating and accreting, can indeed cross the magnetic field lines. Such a resistivity has to be anomalous and is expected to arise from MHD turbulence. Actually, the main assumption of the model is that such a turbulence can indeed be described by local phenomenological transport co-efficients (resistivity, viscosity and heat conductivity). Within this framework, it has been found that steady-state jets require a magnetic field close to equipartition ($\frac{B^2}{\mu_0} \sim P$, where P is the plasma pressure). The magnetic field cannot be stronger otherwise it would forbid ejection. Indeed, the vertical component of the Lorentz force pinches the disc and the *only* force pushing matter up is the vertical gradient of the plasma pressure. This occurs at the disc surface where matter can still cross the field lines (Ferreira and Pelletier (1995)).

For adiabatic or isothermal magnetic surfaces, the ejection efficiency is always very small, typically $\xi \sim 0.01$ (Ferreira (1997), Casse and Ferreira (2000a)). However, if some additional heating occurs at the disc surface, enhancing there the plasma pressure gradient, then much higher ejection efficiencies can be reached, up to $\xi \sim 0.5$ (Casse and Ferreira (2000b)) ! This fact introduces a tremendous complexity in the theory, since knowing the ejection efficiency ξ requires now to solve a realistic energy equation. This is however very promising since it offers a quite natural explanation of why different classes of astronomical objects may produce jets with different efficiencies.

The theory of accretion discs driving jets is now well established, in the sense that both the relevant physical processes and parameter space are known. However, there is still some "freedom" since the ejection efficiency ξ is actually determined by the unknown MHD turbulence parameters (Casse and Ferreira (2000a), (2000b)). Either one gets these parameters from a theory of MHD turbulence inside discs (a dreadfull task), or one uses observations to infer these values.

This is the approach used by Garcia et al. ((2001a), (2001b)). The energy equation and ionization equilibrium have been computed along each magnetic field lines, using a self-similar disc-wind model heated by ambipolar diffusion (neutrals-ions collisions). It was

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[4]Self-similarity is a special case of the method of separation of variables commonly used in mechanics. It allows to solve the full set of MHD equations without any approximation.

then possible to reproduce synthetic observations: spatially resolved forbidden line emission maps, long-slit spectra, as well as line ratios. Line profiles and jet widths appeared to be good tracers of the wind dynamics and collimation, whereas line ratios essentially trace gas excitation conditions. All the above diagnostics were confronted[5] to observations of T Tauri star microjets, with a very nice general agreement. However, it was found that jets with $\xi \sim 0.01$ are too tenuous and with too large velocities[6]. Thus, a detailed comparison with observations shows that T Tauri stars jets require higher disc ejection efficiencies, thereby discs with a warm chromosphere or corona. Such an effect may well be the natural outcome of disc illumination by both UV and X-rays produced by the accretion shock and star itself (see Feigelson and Montmerle (1999)).

But one should also realize that "cold" jets, ie. jets produced by the sole magneto-centrifugal force, are an extravagant theoretical simplification. Indeed, there is no physical reason why thermal effects should play no role, especially in view of its enormous importance in the solar wind. Moreover, at the surface of a magnetized accretion disc, one expects strong energy dissipation due to the presence of both small scale magnetic loops and differential rotation. Hence, any disc producing jets should have a magnetically heated corona (see also Kwan (1997)).

3.   Accretion–ejection from the star–disc interface

Even if accretion discs produce jets, only 1 to $\sim 10\%$ of their mass is being actually ejected. Thus, most of the mass accreting through the disc will eventually fall into the star. Not much freedom is therefore left for our imagination:

● **If stellar magnetic fields are "weak"**, then we expect the formation of an equatorial boundary layer between the disc and the star (Regev and Bertout (1995), Popham et al. (1996)).

● **If stellar magnetic fields are "strong"**, then we expect the disc plasma to be forced to follow the stellar magnetospheric field, giving rise to so-called accretion curtains (or funnel flows, Edwards et al. (1994)).

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[5]Convolution by the observing beam is essential for a meaningful test of the models.

[6]The maximum asymptotic velocity is $v_j \simeq \Omega_o r_o \xi^{-1/2}$, where $\Omega_o r_o$ is the keplerian speed at the footpoint of the magnetic field line.

3.1.   Why is a magnetic interaction zone necessary ?

The "weak field" scenario has a drawback which may be quite severe. Indeed, all T Tauri stars are observed to rotate at about 10% of their break-up velocity (Bertout (1989)). This means that matter reaching the equator is rotating much faster than the star. Thus, such a meridional boundary layer can only lead to a stellar spin-up. But the current interpretation of observations is that accreting T Tauri stars (ie. CTTS) maintain a constant period and, once their disc has disappeared (ie. WTTS), their own gravitational contraction makes them spinning up (Bouvier et al. (1997), Bouvier, Forestini and Allain (1997)). This implies that the coupling between the star and the disc must brake down the contracting star and remove both accreting material and its own angular momentum.

One could argue that the star, viscously linked to the surrounding disc, is simultaneously driving a wind that carries away this angular momentum. But to my knowledge, no conventional stellar wind model ever showed that it could indeed produce such a strong magnetic braking. Moreover, if the star is able to produce such a stellar wind, then it surely has also a magnetospheric field threading the circumstellar disc. One has therefore to explain why such a configuration has no dynamical influence on the disc (no relevant torque, no "freezing" action on the required MHD turbulence).

We are therefore lead to assume there must be a magnetospheric interface between the star and its accretion disc. Such a conclusion is fortunately supported by several observational pieces of evidences: measures of strong stellar magnetic fields (of order kG, Guenther et al. (1999)), emission lines probing infalling matter from high latitudes (Beristain et al. (2001)), photometric variability and obscuration (Bouvier et al. (1999)), holes in the innermost disc region (Muzerolle et al. (1998) and references therein).

3.2.   An "extended" or a "narrow" interface ?

We saw that the disc and the star are dynamically linked by large scale magnetic fields in such a way that the contracting star is being spun down. The question now is to find the correct magnetic configuration. Let us first introduce two important definitions:

• **The corotation radius**, namely $r_{co} = (GM_*/\Omega_*^2)^{1/3}$, is defined as the radius where the keplerian rotation is equal to the stellar one (note that disc material is always slightly sub-keplerian).

• **The magnetopause radius** r_m is defined as the equatorial radius below which there is no disc plasma anymore, only the force-free stellar magnetosphere.

The respective location of these two radii plays an important role in the star–disc interface dynamics. There are two extreme magnetic configurations that must allow accretion towards the central star and provide a magnetic braking: (1) an "extended" interface, which is a situation where stellar field lines thread the accretion disc on a wide range of radii, from r_m to a much larger outer radius; (2) a "narrow" interface where this outer radius is (larger but) of the same order than r_m.

The extended configuration assumes a (turbulent) disc magnetic diffusivity so that stellar field lines can indeed thread the disc over a large extension (Gosh and Lamb (1978)). All stellar field lines anchored in the disc at a radius smaller than r_{co} produce a spin-up, whereas those anchored beyond r_{co} produce a spin-down. Inside this framework, magnetic braking of the star can in principle be achieved if the magnetospheric star–disc link is such that the two torques almost balance each other (Cameron and Campbell (1993), Li (1996)). Usually, it is found that $r_m < r_{co}$ but close to it, otherwise the spin-up torque would be too large. However, as Bardou and Heyvaerts ((1996)) showed, accretion inside the disc requires a viscous torque greater than that due to the stellar field lines. As a consequence, the consistent magnetic diffusivity must be so large that, instead of being maintained at the same radius (producing thereby a spin-down torque), the magnetospheric field lines inflate (Aly's theorem (1984)) and diffuse rapidly outside the disc. The configuration envisionned cannot simply be sustained.

It seems therefore more natural to expect a sharp transition from the force-free magnetosphere to the star-disconnected accretion disc, ie. a "narrow" star–disc interface. This is much harder to model since it involves strong gradients in both radial and vertical directions. This sharp transition requires $r_m \geq r_{co}$ in order to provide only a negative torque (magnetic braking), ie. a disc truncated at quite a large distance from the stellar surface $R_\star$ (the minimum distance would be $r_m \simeq r_{co} \simeq 3R_\star$). This arises only from the constraint that the star–disc interaction must provide a magnetic braking *on stellar timescales* (10^5 to several 10^6 yrs), much longer than the local disc dynamical timescale (days). How does the system maintain $r_m \geq r_{co}$ on these long timescales is still an open question.

4. The Reconnection X-wind model

4.1. Formation of a magnetic neutral line

Both theoretical and observational arguments point towards the following picture: accretion discs are truncated at $r_m \geq r_{co}$ by stellar magnetospheres whose radial extension inside the discs are quite narrow. There is however something weird about this picture. If

the disc has to be the reservoir of the stellar angular momentum, then how can accretion take place ? Discs are much less massive than the central star so it is quite hard to imagine they will cope with the huge stellar torque and quietly carry away (by radial viscous transport) the excess angular momentum deposited by the star. In the X-wind model, such a transport is assumed to be provided by viscosity around the magnetopause, so that this excess is finally carried away out of the disc by the X-wind (Shu et al. (1994)). But this X-wind is nothing more than a disc wind, capable only to transport the exact amount of angular momentum that allows disc plasma to accrete. In other words, *one cannot drive a jet with stellar rotational energy if the field lines are anchored in the disc.* So, understanding the accretion–ejection physical process leads us to favour a "stellar wind" as the final reservoir for the stellar angular momentum.

Still, observed jets are probably of no stellar origin. But if jets are indeed produced by the circumstellar disc, then the large scale magnetic field in the disc has to match in some way the stellar magnetospheric field. We already know that such a matching has to occur in a narrow region around r_m, where it is reasonable to assume a stellar magnetic field of dipolar structure. Now, if the stellar magnetic moment is oriented in the same direction as the disc magnetic field then one gets a situation where both magnetic fields cancel each other (Figure 1). This leads to the formation of a magnetic neutral line[7] at the axial distance r_X, defined as $B_\star(r_X) = B_{disc}(r_X)$ (Ferreira et al. (2000)).

This neutral line is an azimuthaly extended reconnection zone: closed magnetospheric field lines are being "converted" into open field lines linked to the star. If the disc turbulence is indeed able to sustain the amount of magnetic resistivity required, then such a picture could well be a (time-averaged) representation of a star–disc interface. Note that this reconnection line is located in the disc equatorial plane, so that it is not clear whether or not it could be observed as some X-ray activity (ie. flares related to the presence of a disc).

4.2. Extraction of stellar angular momentum by a wind

Where would this magnetic X-point be located in the disc ? A reasonable answer is provided if we demand that the model satisfies (on a time-averave sense) all the following constraints: narrow interface at $r_m \geq r_{co}$, magnetic braking by a stellar wind and jet

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[7]In this simplified picture, the magnetic moment is aligned with the stellar rotation axis, leading to an axisymmetric neutral line. But this process (and its consequences) remains valid if the dipole is misaligned. In this case, the magnetic neutral line breaks into two oppositely directed angular sectors with a magnetic neutral segment.

formation from the circumstellar disc. The last constraint tells us that the disc magnetic field must be close to equipartition, namely $B_{disc} \propto \dot{M}_{acc}^{1/2}$. The first constraint obviously imposes $r_X > r_m \geq r_{co}$. Using some crude prescription for the stellar magnetic field, namely $B_\star \propto r^{-n}$ ($n \geq 3$ free and mimicking a "compressed" magnetosphere), then one gets the value of the stellar magnetic moment, which can then be compared to observations.

The remarkable property of such a configuration is that magnetic braking is automatically achieved. Indeed, at radii greater than r_X, disc plasma is unaware of the star and its dynamics is exactly the same as in an accretion–ejection structure. But around r_X a sharp transition occurs: matter on the disc equatorial plane crosses the magnetic neutral line and is deflected vertically by the vertical Lorentz force to form accretion curtains (at $r_m < r_X$ all disc material has been deflected). But matter which is already located at the disc surface is pushed vertically away and loaded onto newly opened field lines. Now, those lines are rotating at the stellar angular velocity which is greater than that of the plasma (as long as $r_X > r_{co}$). This means that this material is experiencing a "magneto-centrifugal" acceleration from the star ! Hence, the star itself is indeed powering (with rotational energy and angular momentum) plasma that was originally inside the disc. Since plasma is being loaded at r_X and not at $R_\star$ as in conventional stellar winds, we call these winds "Reconnection X-winds".

It is noteworthy that such ejection events at the star–disc interface are most probably time-dependent. They are indeed highly dependent on the fact that $r_X > r_{co}$ and on the local magnetic topology, which itself depends on both stellar dynamo and disc MHD turbulence. So, we expect that such a configuration is actually producing accretion–ejection events in some intermittent way, involving short (days: MHD turbulence) to quite long (years or more: stellar dynamo) timescales. Since every ejection event is channeled by the surrounding disc-wind, it would observationaly appear as a "collimated" bullet.

Such a configuration is especially useful for the very early phase of the star (embedded protostar, Class 0 and I). Indeed, once optically visible, the star rotates at only 10% of its break-up velocity. This means that stellar material, that originally came from a molecular cloud, already lost a huge amount of specific angular momentum. To my knowledge, such an efficient angular momentum extraction has never been obtained during the collapse itself. It can be shown however that Reconnection X-winds can very efficiently brake down a contracting protostar (from break-up to 10% of it), on timescales compatible with the duration of the embedded phase (Ferreira et al. (2000)).

4.3.   Fossil fields and early stellar dynamo

To summarize, we suppose that a non-negligible fraction of the magnetic flux carried by the parent molecular cloud remains trapped during the formation of the protostellar core. The result is a protostar with a magnetic moment parallel to the magnetic field threading the newly formed surrounding accretion disc. We expect that in the innermost region of the disc the magnetic energy will be close to equipartition with the disc thermal energy, initiating jets from the disc itself. We further suppose that a stellar dynamo begins to operate in the rapidly rotating convective protostar. In contrast with usual stellar dynamo models, the protostar is in contact with an accretion disc which itself carries a remnant magnetic flux. Note that by contact, we mean transfer of both mass and angular momentum: the behaviour of such dynamos has not been studied yet. We therefore speculate that the particular boundary conditions provided by the magnetized disc will favour growing dynamo modes with a magnetic moment aligned with the disc field (on a quasi-stationary regime)[8].

Although this is a speculation, it is quite natural to envision protostar evolution as being strongly influenced by both initial (presence of strong fossil fields) and boundary (circumstellar accretion disc) conditions. Such a speculation leads to Reconnection X-winds, that may solve the angular momentum problem in star formation. If this picture is viable, then dynamo theory would have to be revisited, for a protostar could no longer be treated as a convective star in vacuum.

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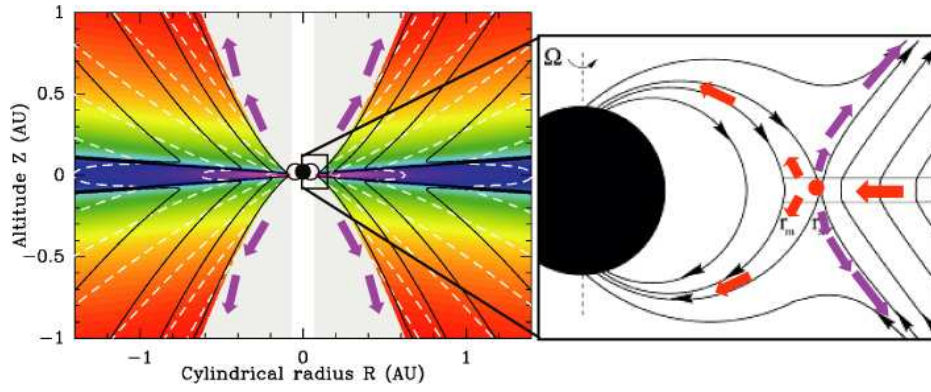Wardle, M. and Konigl, A. 1993, ApJ, 410, 218

Fig. 1.— Left: self-collimated jets from a keplerian accretion disc, with streamlines (black solid), contours of equal total velocity (white dashed) and density stratification in grayscale (Ferreira (1997)). Right: sketch of the magnetic configuration leading to "Reconnection X-winds" above the magnetic neutral line. Arrows show the expected time-dependent plasma motion (Ferreira et al. (2000)).